Quark, Lepton, CP Colloquium

Answers to “Tough Questions”

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The "tough questions"

IF18 Is there a target level of precision for the measurement of heavy quark observables? To what level should such measurements continue to be pursued in the absence of deviations from SM expectations?

IF19 If the LHC does not discover new physics, what can be learned from more precise measurements in the quark flavor sector?
What level of precision is desirable for neutron, electron and atomic EDM experiments in this scenario?

IF20 Describe the increase in sensitivity to new particles in loops as a function of time for the g-2, μ - e conversion, $\tau \rightarrow \ell\gamma$, and EDM experiments.
There should be separate estimates for SUSY models, in which the flavor-changing effects come from loops, and from models in which the flavor-change comes from a tree-level effective operator. This will facilitate plotting this evolution along with the evolution in sensitivity predicted for direct searches for new particles at the LHC.

IF26 Does the strong upper limit on the $\mu \rightarrow e\gamma$ branching ratio from MEG preclude an observable signal of lepton flavor violation in μ - e conversion experiments in nuclei? What new physics could such a signal reveal?

Required precision and relevance of heavy quark observables

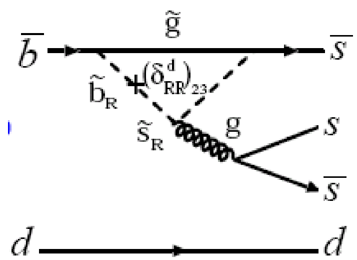
- There are two aspects
  - The size and precision of theoretical calculations for a given quantity
  - The achievable experimental precision for a given variable
- The size of new physics effects is mass scale-dependent
  - Even with LHC mass limits, many observables provide strong constraints on BSM models
  - If particles are found and masses determined, then the conversation between LHC and indirect studies can lead to an understanding of the details of what has been found
- If LHC does not discover new physics, the search for indirect effects provides the basis of a strong experimental program
  - The pattern of effects can tell us a great deal about the class of SUSY-breaking or extra dimension models that might still be relevant

squark mass matrix (d sector)

LHCb, Belle-II, τ/c

$$\begin{pmatrix} m^2_{\tilde{d}_L} & m_d(A_d-\mu\tan\beta) & (\Delta^d_{12})_{LL} & (\Delta^d_{12})_{LR} & (\Delta^d_{13})_{LL} & (\Delta^d_{13})_{LR} \\ & m^2_{\tilde{d}_R} & (\Delta^d_{12})_{RL} & (\Delta^d_{12})_{RR} & (\Delta^d_{13})_{RL} & (\Delta^d_{13})_{RR} \\ & & m^2_{\tilde{s}_L} & m_s(A_s-\mu\tan\beta) & (\Delta^d_{23})_{LL} & (\Delta^d_{23})_{LR} \\ & & & m^2_{\tilde{s}_R} & (\Delta^d_{23})_{RL} & (\Delta^d_{23})_{RR} \\ & & & & m^2_{\tilde{b}_L} & m_b(A_b-\mu\tan\beta) \\ & & & & & m^2_{\tilde{b}_R} \end{pmatrix}$$

LHC



$$\left(d^d_{ij}\right)_{AB} = \frac{\left(D^d_{ij}\right)_{AB}}{\tilde{m}^2}$$

- Different processes have different experimental and theory sensitivities
  - A_{CP} due to hadronic B decays proceeding via $b\to s$ penguins: $S_{\psi Ks} - S_{\phi Ks}$
    - Time dependent A_{CP} in $K_S\pi^0\gamma$
    - $\Delta A_{X_s\gamma} = A_{B^\pm\to X_s\gamma} - A_{B^0/\bar{B}^0\to X_s\gamma}$
  - $B_{d,s}\to\mu^+\mu^-$, ..
  - Tree level unitarity triangle observables
  - D^0 mixing, CPV

LHC mass limits may make some effects difficult to observe
- Others still provide Powerful constraints

Flavor studies provide a "DNA Chip" for New Physics

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0-\bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B\to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B\to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B\to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B\to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s\to\mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+\to\pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L\to\pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu\to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau\to\mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu+N\to e+N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

The pattern of measurement:
★★★ large effects
★★ visible but small effects
★ unobservable effects
is characteristic,
often uniquely so,
of a particular model

GLOSSARY	
AC [10]	RH currents & U(1) flavor symmetry
RVV2 [11]	SU(3)-flavored MSSM
AKM [12]	RH currents & SU(3) family symmetry
δLL [13]	CKM-like currents
FBMSSM [14]	Flavor-blind MSSSM
LHT [15]	Little Higgs with T Parity
RS [16]	Warped Extra Dimensions

W. Altmannshofer, A.J. Buras, S. Gori, P. Paradisi and D.M. Straub, *Anatomy and Phenomenology of FCNC and CPV Effects in SUSY Theories.* *Nucl.Phys*. **B830**,17 (2010).

Models of CLFV have characteristic patterns

ratio	LHT	MSSM (dipole)	MSSM (Higgs)	4G
$\frac{\mathcal{B}(\mu^-\to e^-e^+e^-)}{\mathcal{B}(\mu\to e\gamma)}$	$0.02\ldots1$	$\sim 6\cdot10^{-3}$	$\sim 6\cdot10^{-3}$	$0.06\ldots2.2$
$\frac{\mathcal{B}(\tau^-\to e^-e^+e^-)}{\mathcal{B}(\tau\to e\gamma)}$	$0.04\ldots0.4$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$	$0.07\ldots2.2$
$\frac{\mathcal{B}(\tau^-\to \mu^-\mu^+\mu^-)}{\mathcal{B}(\tau\to \mu\gamma)}$	$0.04\ldots0.4$	$\sim 2\cdot10^{-3}$	$0.06\ldots0.1$	$0.06\ldots2.2$
$\frac{\mathcal{B}(\tau^-\to e^-\mu^+\mu^-)}{\mathcal{B}(\tau\to e\gamma)}$	$0.04\ldots0.3$	$\sim 2\cdot10^{-3}$	$0.02\ldots0.04$	$0.03\ldots1.3$
$\frac{\mathcal{B}(\tau^-\to \mu^-e^+e^-)}{\mathcal{B}(\tau\to \mu\gamma)}$	$0.04\ldots0.3$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$	$0.04\ldots1.4$
$\frac{\mathcal{B}(\tau^-\to e^-e^+e^-)}{\mathcal{B}(\tau^-\to e^-\mu^+\mu^-)}$	$0.8\ldots2$	~ 5	$0.3\ldots0.5$	$1.5\ldots2.3$
$\frac{\mathcal{B}(\tau^-\to \mu^-\mu^+\mu^-)}{\mathcal{B}(\tau^-\to \mu^-e^+e^-)}$	$0.7\ldots1.6$	~ 0.2	$5\ldots10$	$1.4\ldots1.7$
$\frac{\mathrm{R}(\mu\mathrm{Ti}\to e\mathrm{Ti})}{\mathcal{B}(\mu\to e\gamma)}$	$10^{-3}\ldots10^{2}$	$\sim 5\cdot10^{-3}$	$0.08\ldots0.15$	$10^{-12}\ldots26$

Felsmann, et al.

$$A\left(l_i \to l_j\gamma\right) =$$

$$a[Y_e Y_\nu^\dagger Y_\gamma]_{ij} + b[Y_U^\dagger Y_U Y_D]_{ij}$$

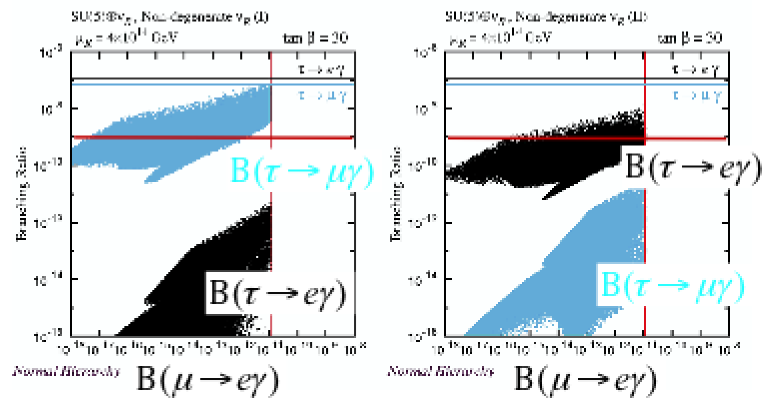
PMNS mixing	CKM mixing
dominant if	dominant if
$M_R > 10^{12}$ GeV	$M_R < 10^{12}$ GeV

$$\boxed{\mathrm{B}(\tau\to\mu\gamma):\mathrm{B}(\tau\to e\gamma):\mathrm{B}(\mu\to e\gamma)}$$

$[500-10]:1:1$	$10^4:500:1$

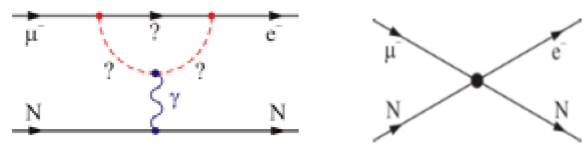
$\mathrm{SU}(5)\oplus\nu_R$ (non-degenerate)

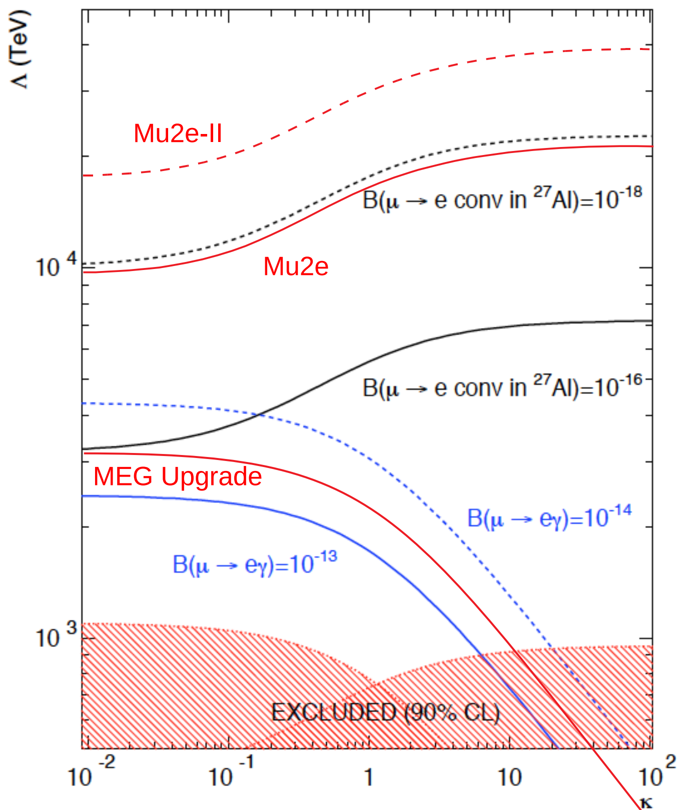
[Goto et al.]

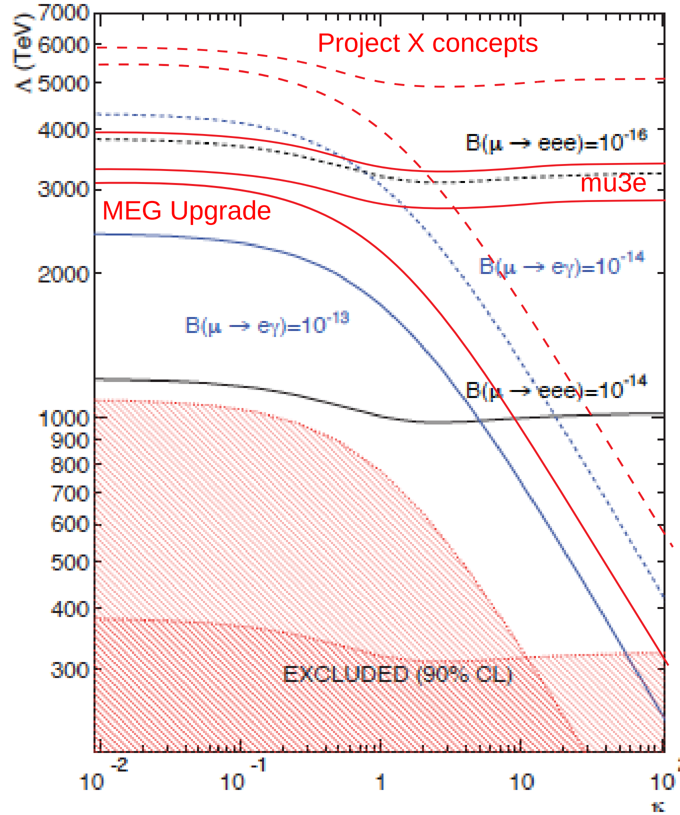


Do improved limits on $\mu \rightarrow e\gamma$ preclude a μ-e conversion signal ?

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right)$$

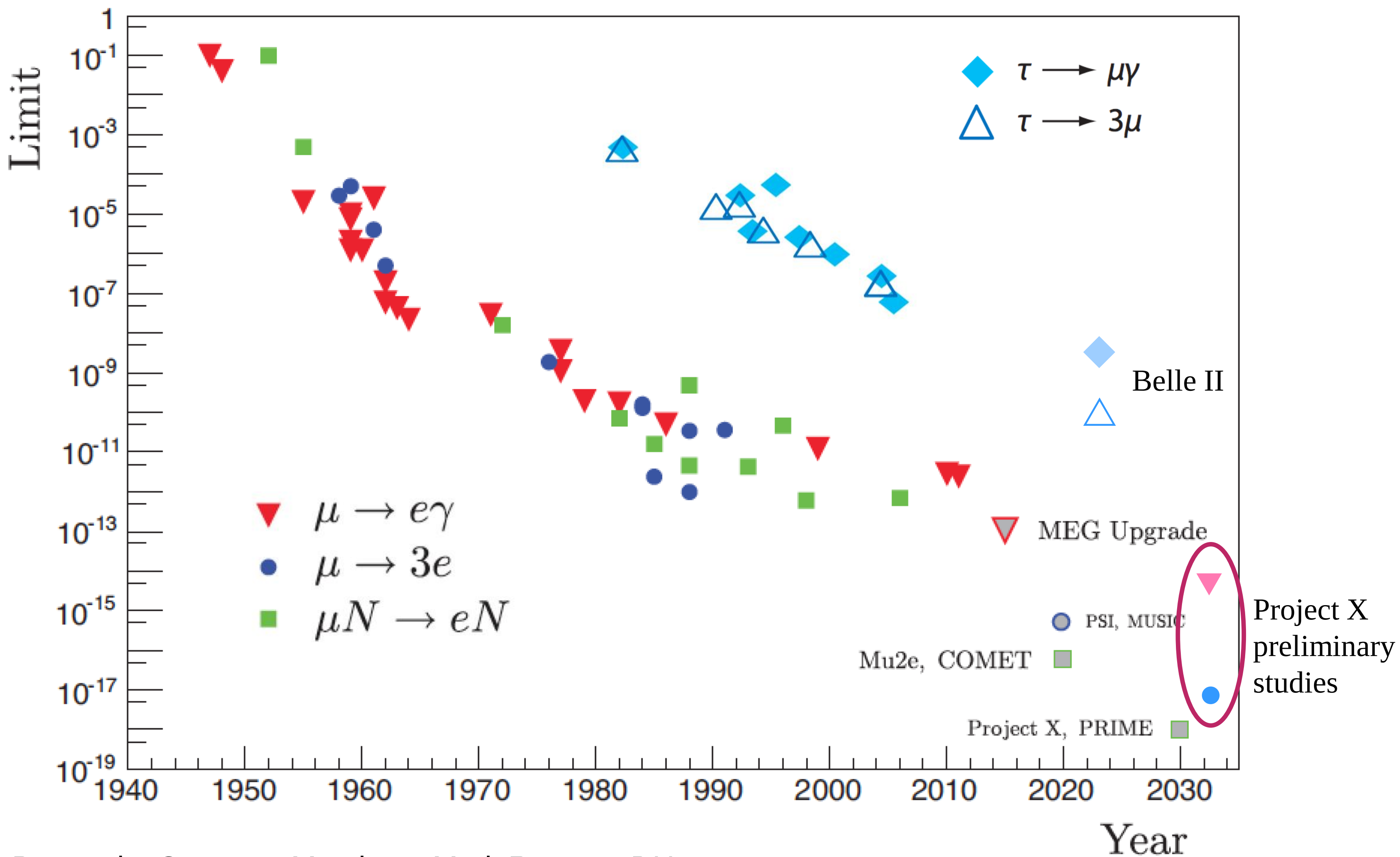






de Gouvêa and Vogel

Improvement in sensitivity of CLFV determinations can directly confront many BSM models



Bernstein, Cooper + Marciano, Mori, Roney + DH